Architecture of the Future Low-Carbon, Resilient, Electrical Power System

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Abstract

The electrical grid which enables our modern way of life was conceived more than 100 years ago. The industrial and consumer loads and generator technologies of the past were all based on alternating current (AC), leading to today's AC electrical network. However, new generation technologies like solar and wind power, as well as electric vehicles (EVs) and battery storage all use direct current (DC). Our appliances, computers, smartphones, heat-pumps and more, as well as common industrial loads, such as variable speed drives, are also mostly DC based. Because of this, many converters are needed to interface generation and loads to the AC grid, creating inefficiency and causing compatibility problems.

A more efficient and sustainable electrical grid is needed which can easily accommodate new renewable technologies. Conveying electrical power by DC reduces losses and lessens voltage drop. A partial transition of our electrical grid to DC has many technological benefits, including more flexible and efficient systems for generation, conveyance, storage and use, as well as easier integration of renewable generation and technologies such as EVs and battery storage.

The electrical grid is a critical player in reducing emissions of both greenhouse gases that lead to climate change, and other pollutants. There is a need to quickly adapt how we produce, use, transport and manage energy, to minimise the impact on the environment. Changes have begun worldwide with initiatives to increase renewable and sustainable electricity generation, uptake of EVs, and electrification of industrial processes. All these reduce fossil fuel consumption and greenhouse gas emissions. However, further initiatives are needed to address the impact on the environment. Many of these initiatives will require a hybrid AC/DC grid — a system which integrates DC conveyance with the existing AC electrical network.

The major research challenge is to determine the future architecture, topology and a transition pathway. As part of the government's Strategic Science Investment Fund on Advanced Energy Technology Platform, the 7-year project "Architecture of the Future Low-Carbon, Resilient, Electrical Power System" has been awarded to address these questions and to develop capability to deliver the transition. This paper will describe the primary workstreams, their research objectives and expected outcomes.

Our team comprises of researchers from the New Zealand (Universities of Canterbury, Auckland, AUT, Victoria, Waikato) and overseas, and dozens of overseas collaborators. Together, the key challenges of the future grid is tackled and technical capability is built, ultimately benefitting every New Zealander.

Introduction

In the late 1880s and early 1890s, the war of currents raged in the United States between alternating current (AC) technology launched by Westinghouse and direct current (DC) technology launched by Edison Electric Light Company. AC was an outright victor with the introduction of transformers that enabled stepping-up and stepping-down of the voltage, improving the efficiency of electricity transmission over long distance; and induction machines which became the cornerstone of multi-phase systems.

The evolution of electronics and power electronics over the past 70 years as well as the introduction of variable renewable energy sources such as solar, wind etc. and electro-chemical (battery) energy storage, has once again raised the profile of DC for electricity transmission and distribution (T&D).

The programme: "*Architecture of the Future Low-Carbon, Resilient, Electrical Power System*" also known as *Future Architecture of the Network (FAN)* or *Te Whatunga Hiko*, aims to develop the knowledge and understanding of the extent of DC technology and circuit penetration within the existing AC network. It will also address a suitable transition pathway for the New Zealand (NZ) context. The programme has a long time horizon of 2050 and beyond.

Background

33% of global Greenhouse Gas *(GHG)* emissions are due to electricity and heat production [1]. In New Zealand despite 85% of the electricity being generated from renewable sources, the total electricity generation still contributes to 8.8 % of the country's GHG emissions [2]. Globally GHG reductions can be achieved by substituting fossil fuels with renewable electricity. Some initiatives already under way, include integration of renewable and sustainable electricity generation, electrification of process heat, electrification of transportation and new loads, e.g. battery storage and energy-efficient devices such as LEDs. If all road vehicles are electrified, we will save NZ another 39.1% total GHG [2], which will necessitate additional conveyance and potentially generation [3].

At over NZ$15B (e.g. Transpower NZ$5B [4], Vector NZ$ 3.3B [5], PowerCo NZ$2.3B [6], and Orion NZ$1.2B [7]), the NZ electricity network is one of our most valuable assets, enabling our modern way of life. It is also considered instrumental for achievement of a low emission future. This critical asset is aging. Our T&D companies are presently investing NZ$1B/year (e.g. Transpower invests NZ$300-400M/year [4], Vector ~NZ$250M/year [8], PowerCo ~NZ$200M/year [5], Orion ~NZ $100M/year [6]) towards network upkeep. It is the right time to review our electricity system strategically.

The change to widespread electrification and new technologies can lead to increased complexity, randomness and decentralization of electricity transmission and distribution. This can be partially solved with additional energy storage and complex power management technologies. However, there is one major underlying issue: the T&D system itself. The electrical grid which enables our modern way of life was conceived more than 100 years ago and was designed as a monolithic, centralized, frequency synchronized, AC network with unidirectional power flow. But almost all new technology solutions enabling our modern society to transition to low GHG are DC. This duality presents the following issues:

- An AC grid will limit the uptake of more renewable energy and energy efficient devices. Deploying new technology beyond the hosting capacity will result in an inefficient system with serious reliability and stability concerns.
- The losses in the NZ and global electricity T&D system, based on generation output are ~8 % [9, 10]. This translates in global energy waste of the order of 1500 TWh [11]. On top of this we have increasing conversion losses ~ 2-3 % at both the (renewable) generation and end-use (consumer appliances) [12].
- It is possible to integrate PV and wind via inverters into the existing AC networks. Energy storage can alleviate the intermittent nature of the source. However, the penetration level is restricted by the problems that they can introduce for higher renewables (>30-50 %) [13].

Unlike AC circuits, the power flow through DC circuits is controllable, enabling better utilization of the network. It allows maximising the conveyance through a circuit. The main impact of transitioning to increased DC penetration and conveyance is enabling a low carbon and sustainable energy system. Today, the substantial savings in NZ are conservatively estimated as ~NZ$150m/year and reduction in emission of 128.000t CO_2 eq./year.

Future DC generation and loads are fuelled by the substantial progress in efficiency, costs, and uptake of semiconductor power electronics [14]. This is the crucial component of every future DC based grid. The question is not whether DC conveyance and DC systems will have a role in the system moving forward, the questions are where, how and how fast? The transition could take various forms e.g. full DC grid [15], a hybrid AC/DC [16], meshed DC microgrids and decentralized DC communities [17], DC buildings and houses [18], enabling mixed energy economy through storage as energy in electrochemical processes (batteries, fuel cells, even hydrogen) or product. Moving from AC to DC for conveyance is a paradigm shift and we need a better understanding of its many implications. We can see increasing worldwide efforts, initiatives and research programs to address this problem [19].

Regardless of whether conveyance is AC or DC there is an optimal voltage for a given power level and transmission distance. This means there will always be a need to transform the voltage level. Although DC/DC converters exist these at present, and in the foreseeable future, cannot compete with the efficiency and reliability of the AC transformer at high voltage and power levels. Moreover, there is considerable investment already in AC transformers. Therefore the grid of the future is envisaged to be a hybrid AC/DC grid with a high penetration of DC used in it. The aim of this project is to look at the optimum hybrid AC/DC architecture for the future network (Figure 1).

Targeted Research

The research aims to develop an understanding of the extent of DC penetration within the AC systems achievable, the associated challenges, and solutions and also a potential transition pathway. The research outputs will include and are not limited to study methodologies, technologies, inputs to standardisation.

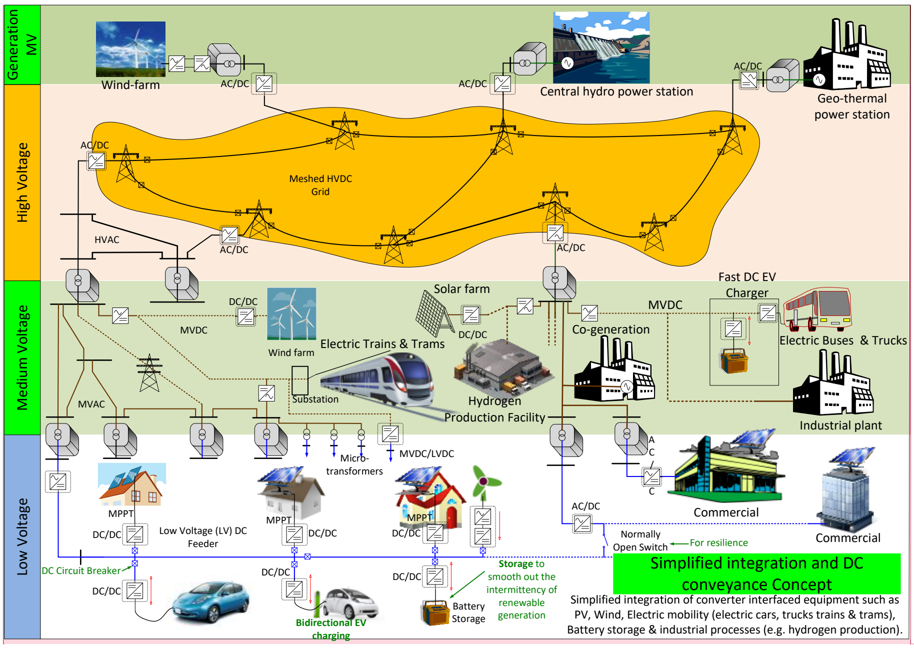

Figure 1. Hybrid AC-DC Concept

Commented [RM1]: This diagram may be simplified. We are looking into this.

This research programme has a long-term horizon of 2050 and beyond, with major knowledge and capability development objectives. It is a technical feasibility study. Considering these objectives the research is not restricted by economic limitations. This enables unconstrained future looking research that will be enhanced by global advances in supporting technologies.

The breadth of the potential research and associated activities are focused through four technical workstreams which attempt to respond to the following:

- To what extent should DC permeate the AC infrastructure?
- How much of the LV, MV and/or MV network should be DC?
- Which circuit topologies maximise the efficiency and benefits offered by DC systems whilst ensuring safety and appropriate protection measures?
- What converter topologies and control techniques are best for the future hybrid network?
- What are the potential barriers with a hybrid AC/DC system?
- What is the transition pathway from AC to DC systems?

Workstreams and Expected Research outcomes

In order to effectively address the research questions the project has been split into four technical workstreams. Three of the four technical workstreams are conceptualised in Figure 2. In addition to technical outcomes the four workstreams will deliver on capability development and work collaboratively with the fifth workstream focused on Vision

Mātauranga (VM). The research programme will aim to leverage pertinent national and international knowledge base and technology.

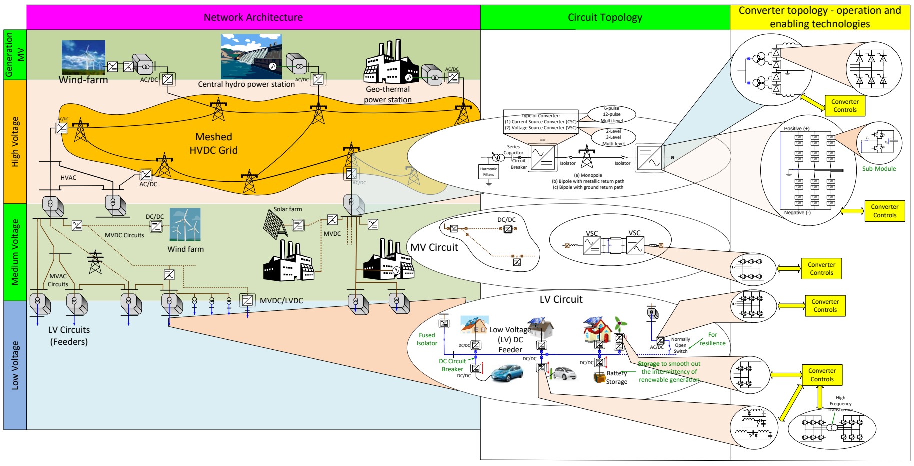

Figure 2. Project workstreams 1 to 3

Workstream 1: Network Architecture

Workstream 1 (WS1) addresses the research at the conceptual level. WS1 objective is to understand the level of DC penetration within the AC network. To achieve this understanding, WS1 will develop techniques digitally model large scale hybrid AC/DC grids in order to evaluate the interactions. The intention would be assess operational steady-state, dynamic and transient interactions between the AC network and distributed converter interfaced technologies and DC systems. This is essential research since, although AC/DC analysis tools exist, they can either address a small part of a system in detail or can look at larger systems and lose the accuracy essential to represent high penetration of DC (power electronics).

WS1 aims to develop methodologies and prototype tools that enable:

- power-flow analysis
- transient and fault analysis
- dynamic analysis

for large scale hybrid AC/DC transmission and distributions networks. These are the key milestones of WS1.

Two PhD projects have been defined to deliver some of the WS1 research:

- Optimum mathematical & computation techniques to enable hybrid network power-flow analysis
- Understanding and modelling low frequency dynamics in a hybrid AC/DC grid

Workstream 2: Topology

Workstream 2 (WS2) investigates the next level down, which is the topology of the circuits that make up the system. The configuration of the circuit and control and protection will be investigated.

WS2 objectives are to determine new DC and AC/DC circuit topologies, considering:

- new fault detection, location and isolation techniques ensuring safety whilst minimising consequent outage
- curtail DC egress into AC networks and
- methods to ensure continued stable operation post fault isolation.

The key milestones for WS2 include:

- Investigation of dedicated DC bus architecture within MV and LV networks; disparate AC/DC converter topologies within DC network; and comprehensively investigated all the necessary control, protection and isolation methods for operating combinations of HV/MV/LV networks within a hybrid AC/DC network.
- Completion of a lab-scale demonstration of DC circuit topology options, working with international and NZ based vendors of DC/AC equipment and safety devices and international standard generating organisations like IEEE and IEC.
- Development of an optimum DC circuit topology regarding control, protection and isolation requirements, working with Electricity Distribution Businesses (EDBs), vendors and AUS/NZ Standard organisations.

Two postgraduate projects have been defined to deliver some of the WS2:

- Design options for Future Hybrid Low Voltage AC-DC Distribution System (PhD)
- Investigation of a hybrid three terminal scheme – a VSC tap in Canterbury on the NZ HVDC link (Masters) – A bridging project along with WS4 with shared learnings and outcomes

Workstream 3: Converter topology, operation and enabling technologies

Workstream 3 (WS3) covers a diverse area under the heading of Converter topology – operation, control and enabling technologies.

WS3 aims to enable proliferation of DC grids within AC grids by addressing technologies and control mechanisms for different power electronic converter configurations:

a) AC-DC converters; interfacing AC and DC networks that essentially convert AC power into DC power and vice versa.
b) DC-DC converters that enable change in DC voltage levels.
c) Converters utilised in ancillary circuits such as DC breakers for circuit isolation

Converter interfaced technologies and thus DC subsystems reduce the network inertia and are prone to interactions. Two solutions will be explored, one reliant on control based on Phase-Lock-Loop (PLL) whose performance will be strengthened through application of advanced control theory, and the other will address design of a control that does not rely on a PLL.

Evolving technologies which form the basis of converter design, such as wide-band gap semiconductor devices, supercapacitors and other electrochemical energy storage will be addressed in collaboration with overseas researchers in the forefront of this area and local expertise.

The key milestones for WS3 include:

- Identification of the state-of-the-art in converter topologies and development of the robust controller and verified the model via simulation. We will investigate the possibility of applying machine learning techniques since the system is going to be very complex and stochastic in nature.
- Development of the prototype a high-power DC breaker for LVDC based on supercapacitors and verify them via experiment.
- Development and build a prototype converter with its advanced control technology to be tested in the AC weak system and verify their effectiveness to enhance the system stability.

One PhD project has been defined to deliver some of the outcomes towards the work stream objectives:

- Control Strategies and Stabilisation Techniques for Converter

Workstream 4: Transition from AC to DC

Workstream 4 (WS4) delivers crucial research suggesting a transition path from the present system to the network of the future. WS4 determine what network infrastructure can be reused in the new system as well as address modifications that may be necessary to AC equipment such as transformers so that they can continue to operate within a system with high DC penetration.

The milestones for WS4 are:

- Modelling and testing use of AC cables, insulators and other system components to enable repurposing for DC.
- Modelling and testing of MV transformers to understand implication of large scale DC penetration (DC ingress, harmonics, large $\Delta V/\Delta t$) and identification of necessary mitigation.
- Development of high frequency models for transformer insulation systems, which are verified via experimentation
- Through modelling and testing development of new mitigation methods for partial discharge due to large $\Delta V/\Delta t$.
- Mitigation measures for DC ingress into repurposed AC equipment.

Two Masters projects have been defined to deliver some of the research outcomes:

- Potential of Low Voltage Direct Current (LVDC) in New Zealand – A transitional Analysis (Bridging project with outcomes shared with WS2)
- Conversion of AC Lines to DC – A New Zealand Perspective

Workstream 5: Vision Mātauranga (VM)

Workstream 5 (WS5) is Vision Mātauranga which contributes to distinctive needs and opportunities for Māori-led businesses and communities. The plan is to partner with different

Māori communities to explore and trial some of the concepts developed as part of the FAN project.

A draft VM Strategy has been proposed in conjunction with Warren Poh (the Māori representative on the research programme Advisory Board (AB)) and is supported by four main pillars:

1. Build and develop VM capability across the key researchers of the programme and across the workstreams
2. Co-development of projects or products which will bring direct impact and benefits for our Māori partners.
3. Build the capability of Māori individuals or groups (iwi, hapū, businesses, etc) to support the increase of number of Māori researchers or businesses in this field.
4. Dissemination and outreach to empower more Māori students in STEM related fields, and especially working in the electricity industry.

The focus in the first year will be on Pillar 1 with two workshops planned for the research team:

- A "full day" Workshop/hui maybe in a Marae – focussed on Māori culture/protocol.
- Bringing VM to Life – A workshop on using VM principles in a Science and Engineering Environment.

For the other pillars, the following actions have been initiated:

- Pillar 2: One Hui (individually) with our Māori rural and urban partners for their inputs into outreach and training activities and develop plan accordingly.
- Pillar 3: Recruit a minimum of two Māori students as part of project development.
- Pillar 4: Develop ideas and implement prototypes for outreach related to the programme. The outreach ideas will be developed through summer student projects and deployed through organisations such as the Otago Museum (Tūhura Science Centre) etc.

Partnerships and Collaborations

FAN is a significant research endeavour and can be delivered successfully only through partnerships and collaborations.

Core Research Team

Our core team comprises of 10 New Zealand-based expert researchers (Universities of Canterbury, Auckland, AUT, Victoria, Waikato) and of 2 overseas contributors (University of Cambridge). This team will deliver research outcomes along with postgraduate (Masters and Ph.D.) and postdoctoral researchers. Top researchers will be attracted through scholarships and fellowships, and development of emerging researchers will be supported, thus investing in people and capability development. The 7-year programme, provides an opportunity for 7 postdoctoral fellows (two year placement each), 18 postgraduate students (PhD and Masters), and over 50 summer students. Gender & ethnic diversity will be encouraged, alongside focus on building and growing Māori capability. Thus investing in future work force.

International Science Collaboration

The research proposal received support from around 15 leading international experts. We will align the expertise with the various workstreams for efficient interaction and endeavour to grow this community further. Knowledge will be shared and outcomes enhanced through research collaborations, researchers' exchange, co-supervision of postgraduate research students to name a few. Learning will be disseminated through joint publications and workshops. Collaborations will be established with complementary international programmes such as the Australian CRC RACE 2030.

A Science Advisor Group (SAG) will be set up from these international experts. It will review the science strategy, science quality and benchmark the science and outcomes, reporting on biennial basis.

Industrial Collaboration

We have identified and consulted with key end-users and beneficiaries in industry and government to confirm our rationale and define the long-term vision of this programme. Seventeen national and international companies have acknowledged the pertinence of the proposed research at the proposal stage. They are keen to be involved and to help us enhance the relevance our research, to deliver and achieve the SSIF investment goals and create long-term benefits for their industry and NZ.

Collaboration with the industries serving the electricity sector is key for the success of the project. This includes the transmission, distribution and generation companies as well as the technology providers. The research will gain value from industry input and learnings will be shared with the industry in the form of technical documentation, methodologies, workshops, contribution to standards, etc.

An Advisory Board (AB) comprising of Industry representatives has been set up. AB will meet twice a year and provide support and guidance to the research team throughout the programme.

Conclusions

It is inevitable that more DC based technologies will enter the system due to the advances in power electronics and numerous benefits these advances provide. Rather than letting the electrical system developing in a haphazard manner, leading to a suboptimal system, it is important to definite the best system to meet our future needs and develop the roadmap to get there. This is an ambition task and one that will require input and active engagement with those in the electricity industry in New Zealand, as well as all our international collaborators. This is a seven year project, and although some collaborators were identified at the project proposal stage, we hope to build upon. Collaboration with those in the electricity industry and overseas universities and institutes is crucial to delivering the best outcome both technically and building capability in New Zealand.

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